Results from the Beam Energy Scan Program at RHIC

Yadav Pandit (STAR Collaboration)

University of Illinois at Chicago

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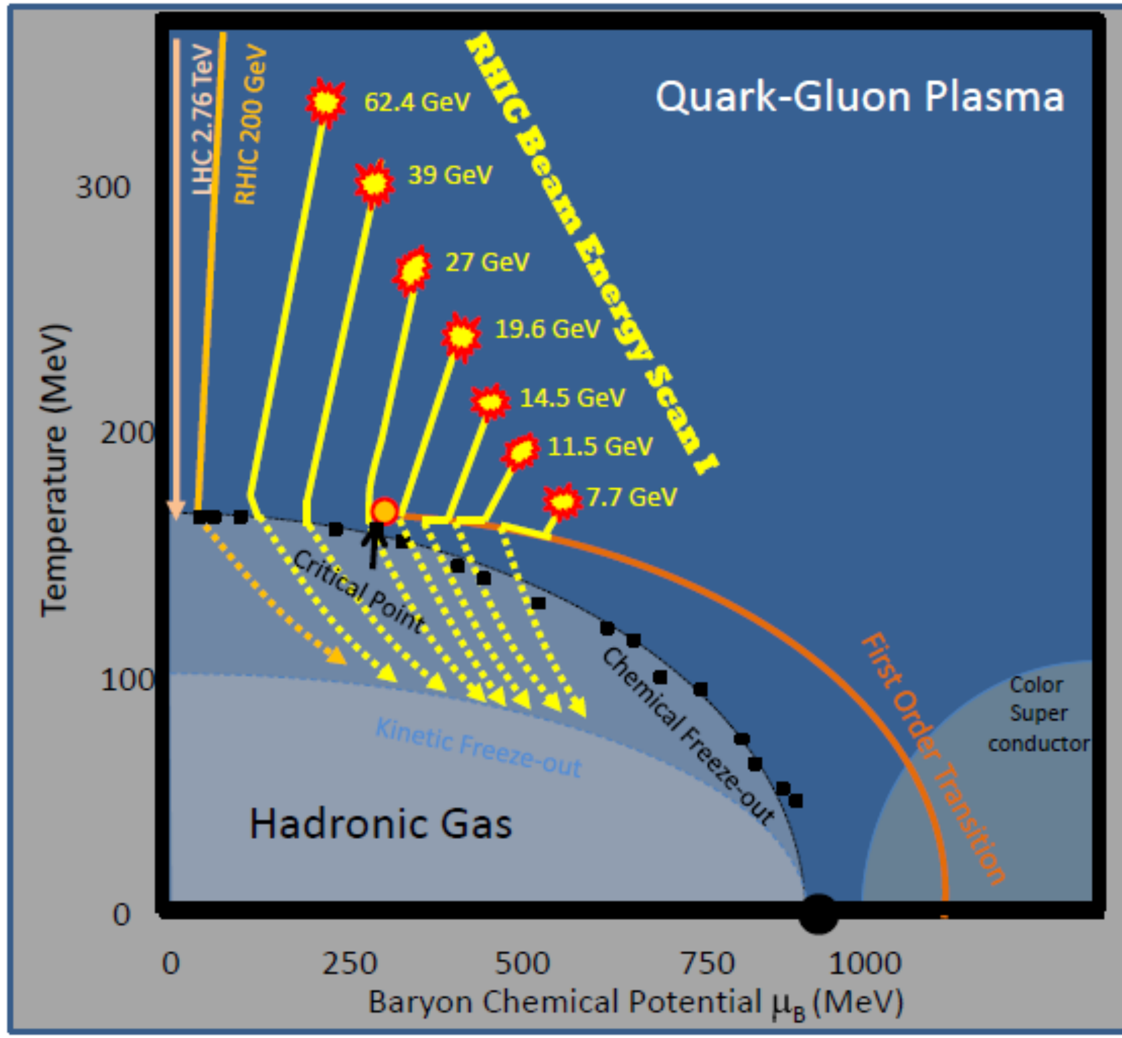
U.S. DEPARTMENT OF ENERGY | Office of Science

BES Program at RHIC

Exploring the QCD phase diagram:

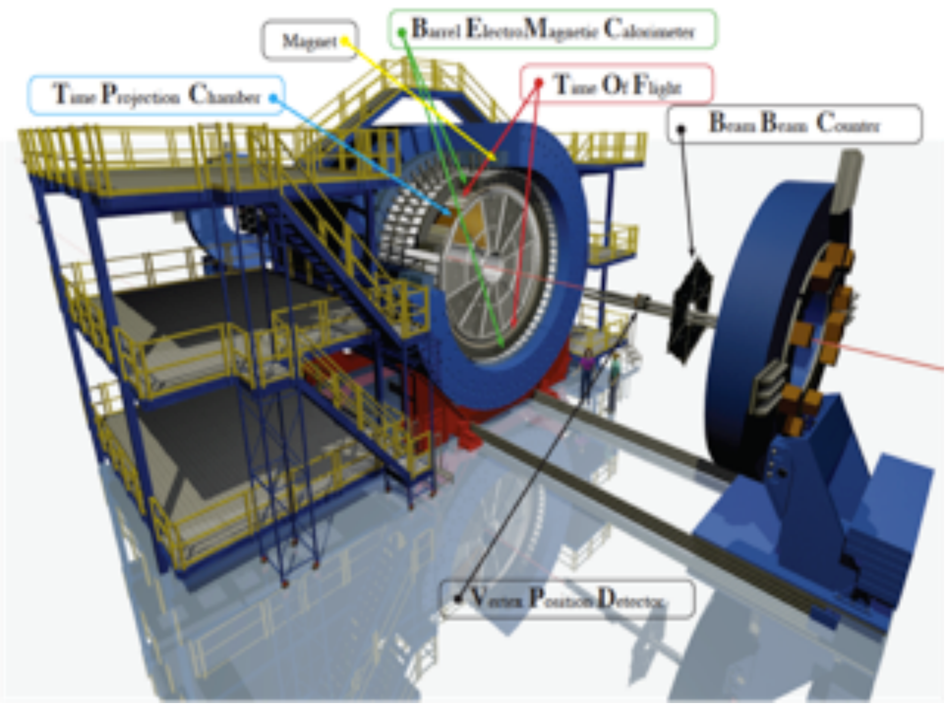
Vary collision energy to change temperature and baryon chemical potential

1. **Search for turn-off signatures of sQGP**
2. **Search for 1st order phase transition from partonic to hadronic phase.**
3. **Search for possible critical point.**



http://arxiv.org/abs/1007.2613

BES Program at RHIC



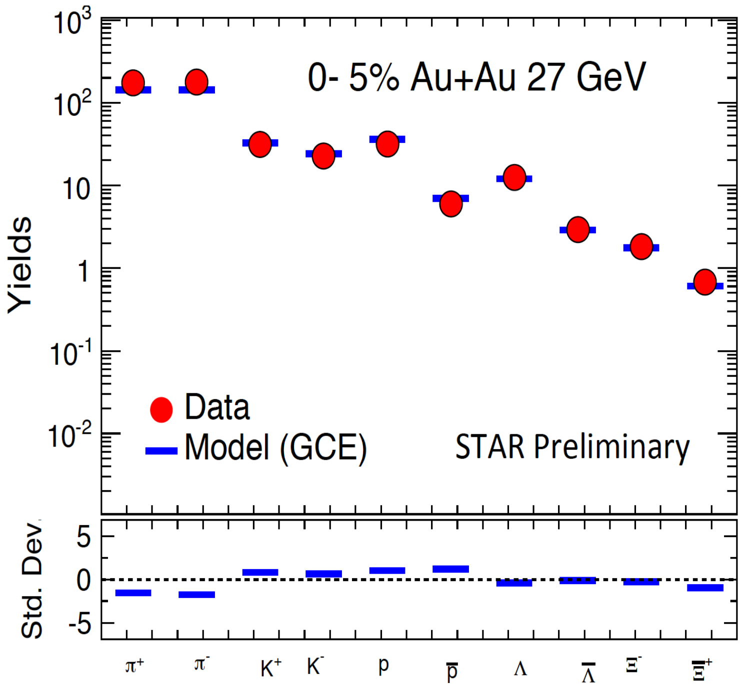
RHIC is uniquely suited to map the QCD phase diagram at finite baryon density

Study of colliding system as a function of:
1) Center-of-mass energy
2) System size

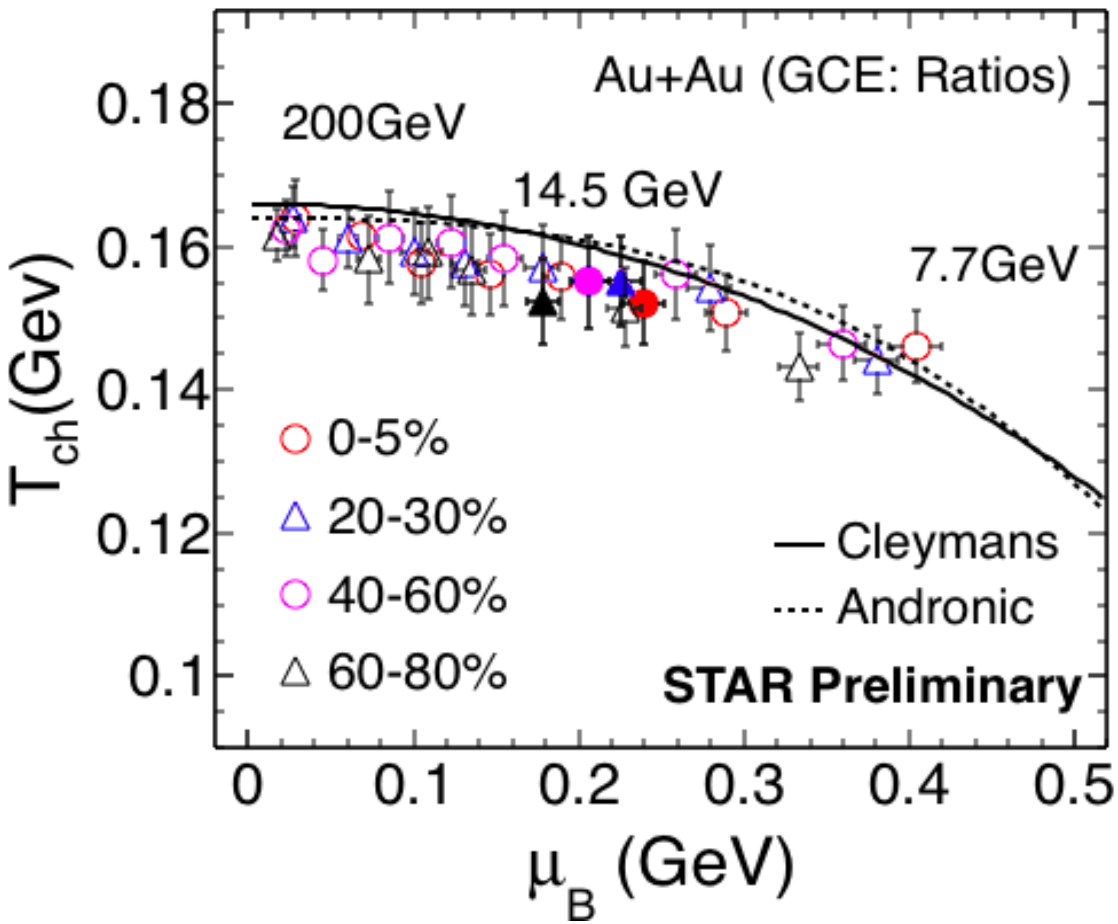
System	Energy
Au+Au	200,130, 62.4, 39,27,19.6, 14.5,11.5,9.2,7.7
Cu+Cu	200,62.4,22
U+U	193
Cu+Au	200
Au+He3	200
d+Au	200, 62.4, 39, 19.6
p+p	200,510, 62.4

Main device for tracking and PID: TPC and TOF
Uniform acceptance: $|\eta| < 1.0$ and $0 < \phi < 2\pi$: coverage
Excellent particle ID: π, K, p through TPC dE/dx aided by TOF
Long-lived particles(K^0_s, Λ, Ξ, Ω) can be reconstructed via topological cuts

Freeze-out Parameters



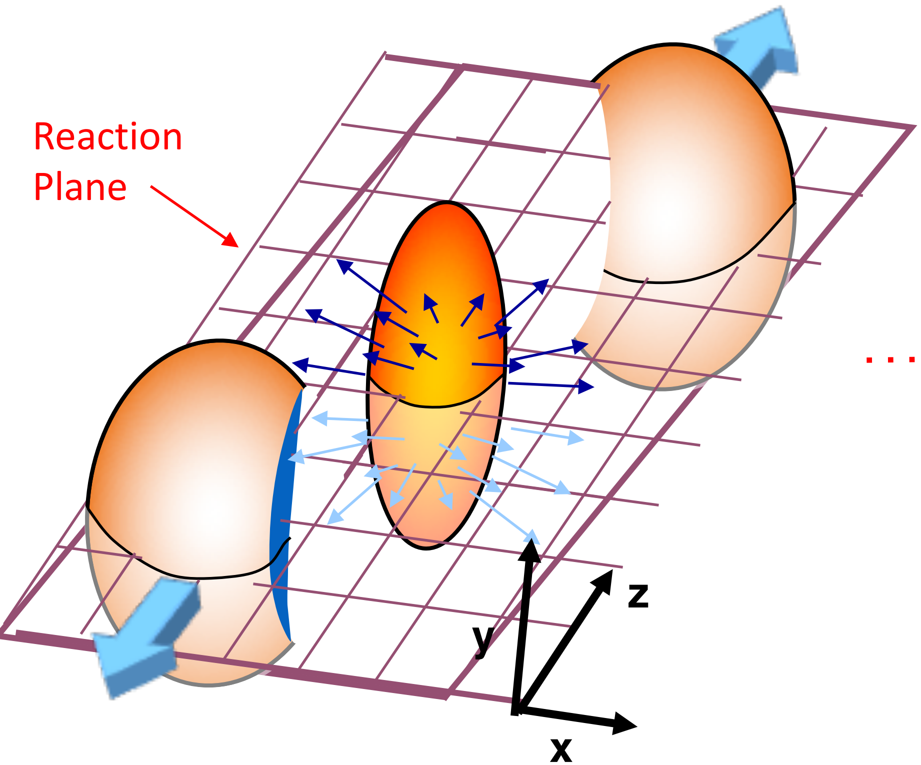
Chemical freeze-out parameter **T and m_B** from particle yields (π, K, p, Λ, Ξ and their anti-particles)

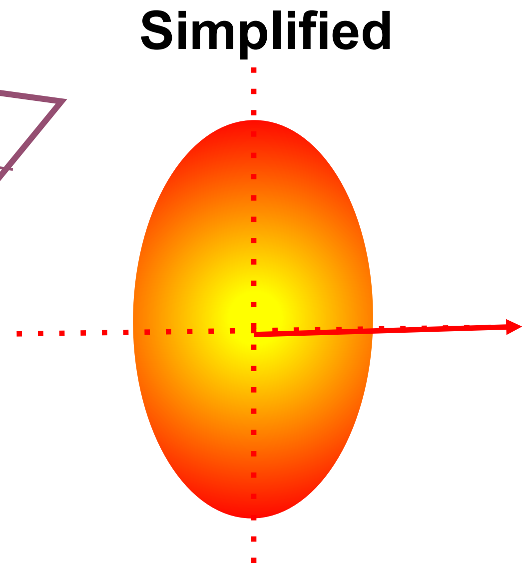


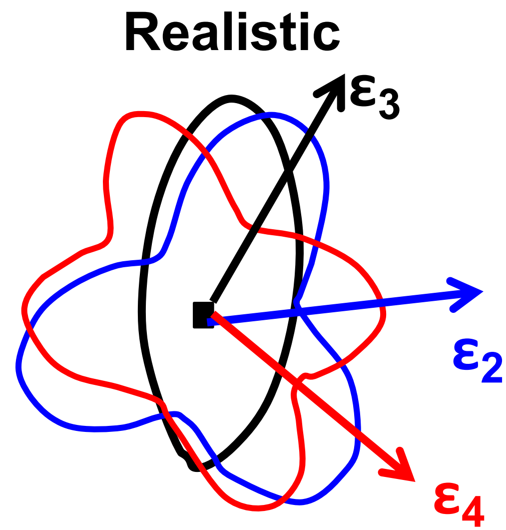
B. Bharati, STAR, QM 2015

- ***J*. Cleymans et al. Phys. Rev. C 73, 034905 (2006)**
- **A. Andronic et al. Nucl. Phys. A 834, 237C (2010)**

Azimuthal Anisotropy







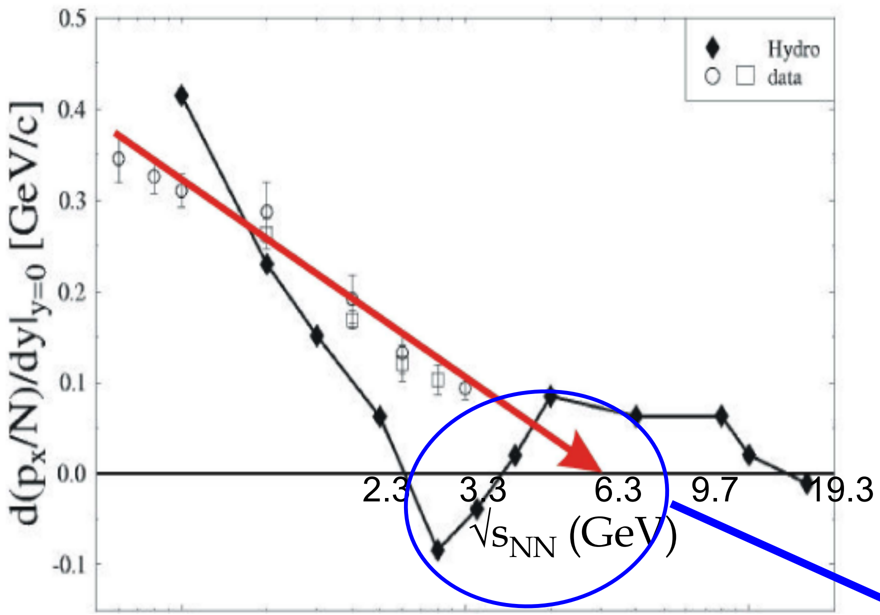
Azimuthal distribution of particles with respect to the symmetry plane

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2v_1\cos(\phi - \psi_R) + 2v_2\cos 2(\phi - \psi_R) + \ldots\right)$$

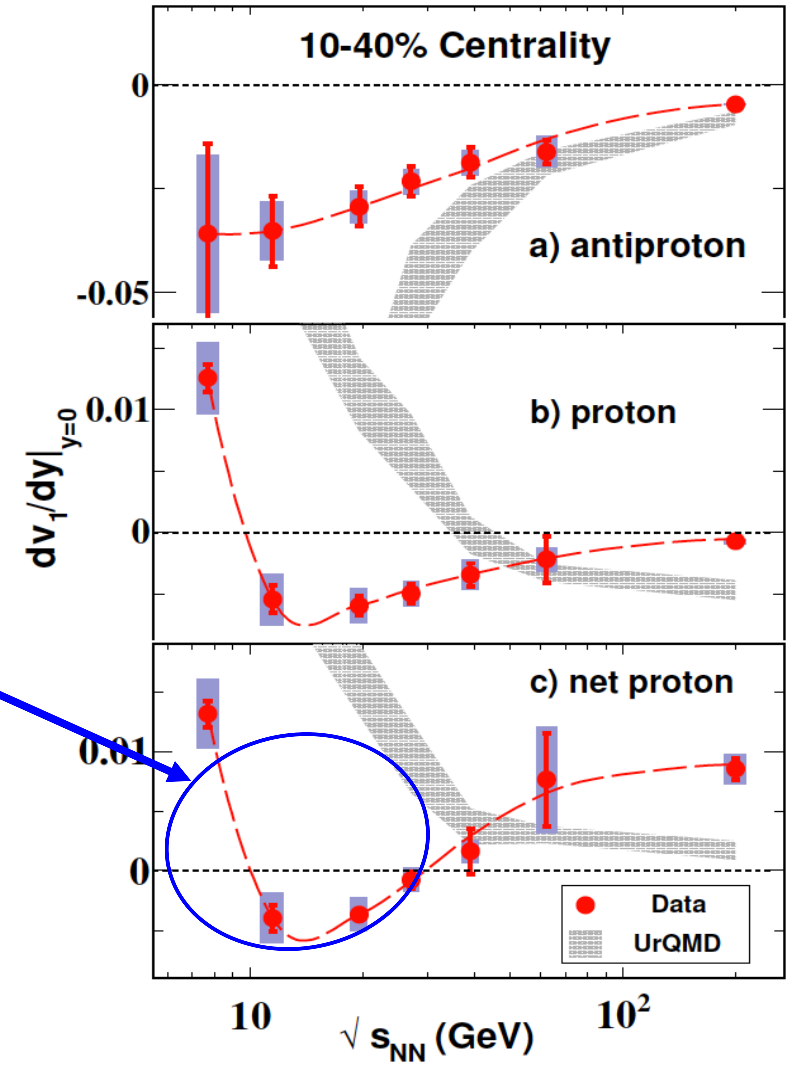
isotropic directed elliptic

Directed Flow (v_1)

H. Stoecker, Nucl. Phys. A 750 (2005)



STAR, PRL, 112, 162301(2014)



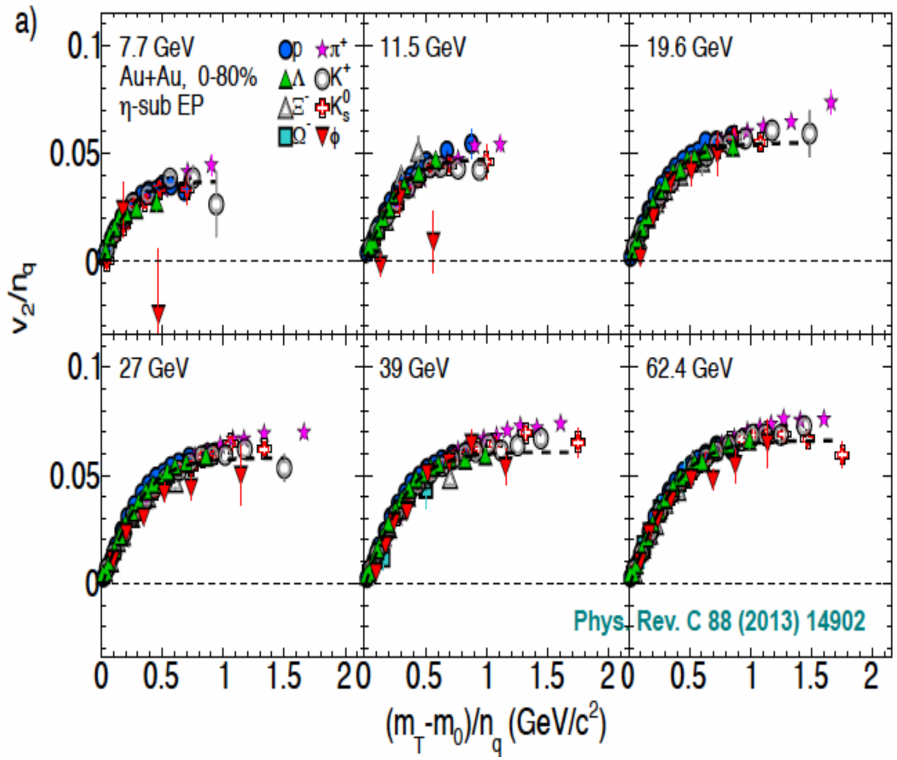
Dip in net-proton dv_1/dy (but different location) resembles theory prediction with a first order phase transition

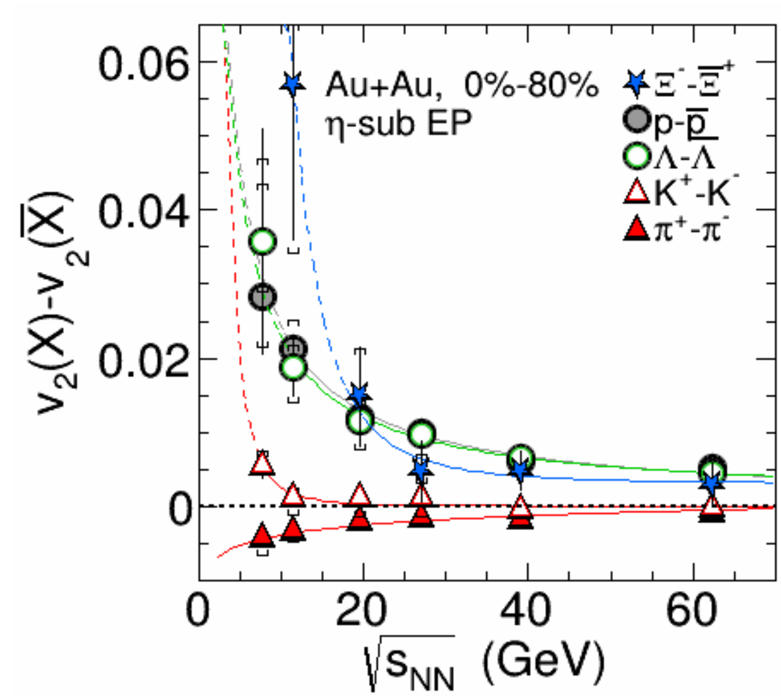
→ Softest point of EoS?

possible hint for 1st order phase transition?

Elliptic Flow (v_2)

STAR, PRL, 110, 142301(2013)

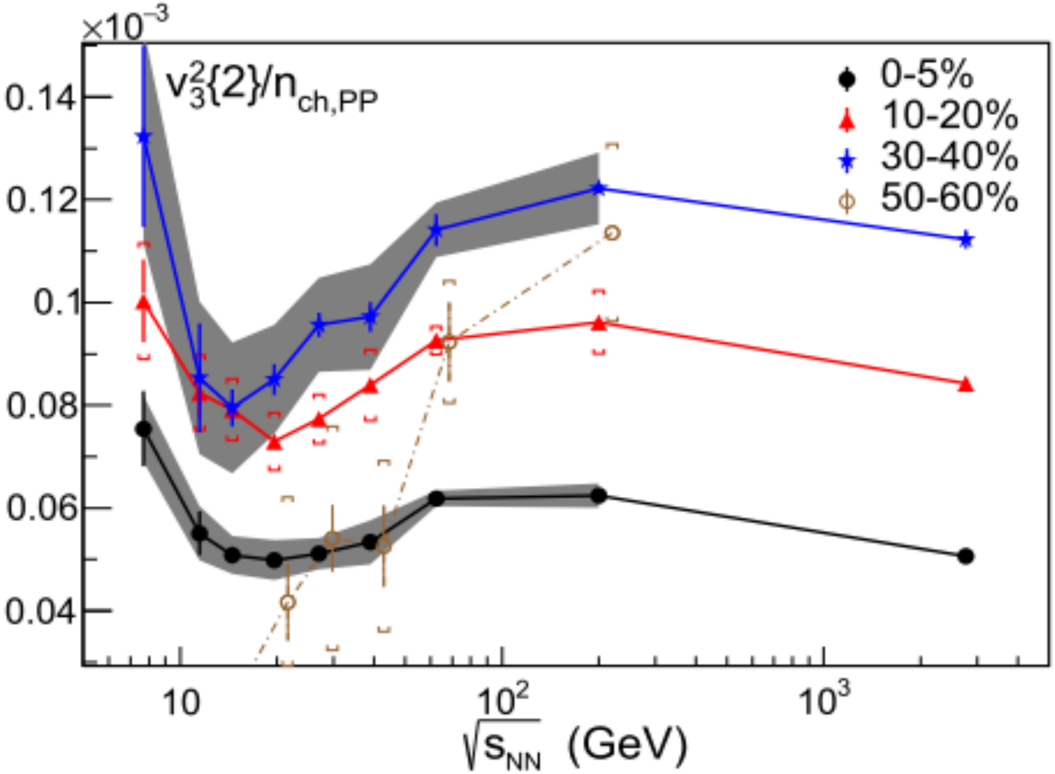


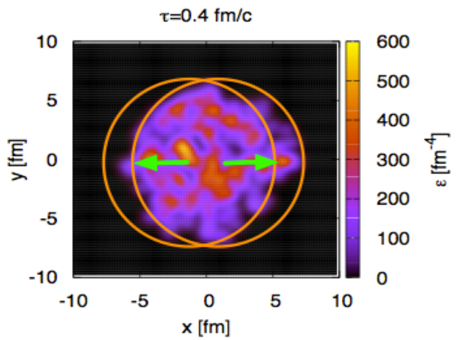


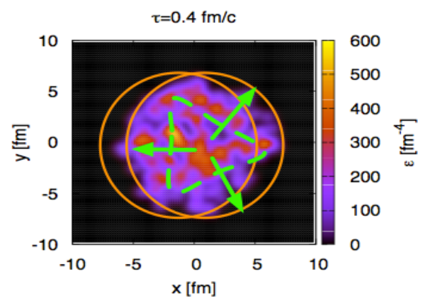
- Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions
- At lower energies, the universal v_2 **NCQ scaling for particle/antiparticle is broken,** Larger split of particle-antiparticle at lower beam energy.
- Consistent with hadronic interactions becoming dominant.

Triangular Flow (v_3)

STAR, PRL, **116**, 112302 (2016)

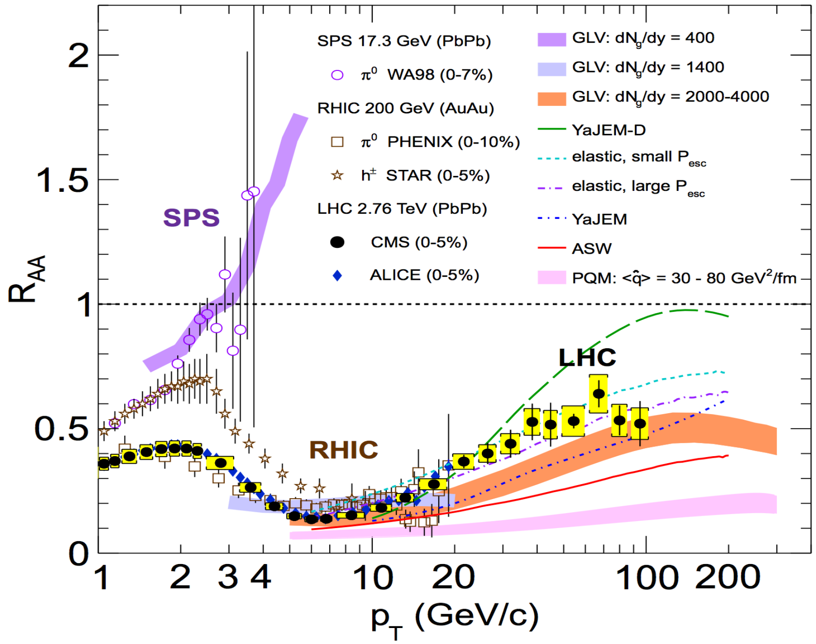


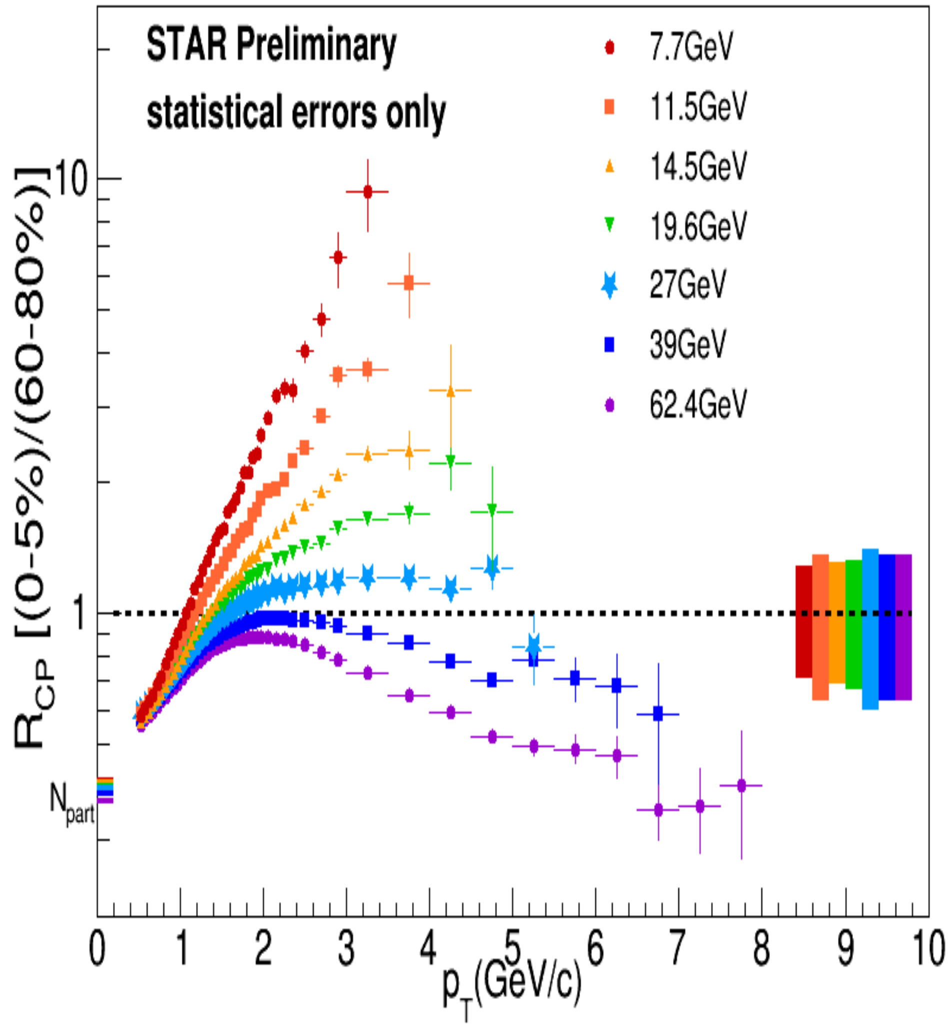




- Sizable v_3 at lower energies at central collisions while for peripheral collisions v_3 is consistent with zero below 14.5 GeV
- v_3 scaled by n_{ch}, local minima at 7—20 GeV. (Softening of equation of state?)

High pT Hadron Suppression

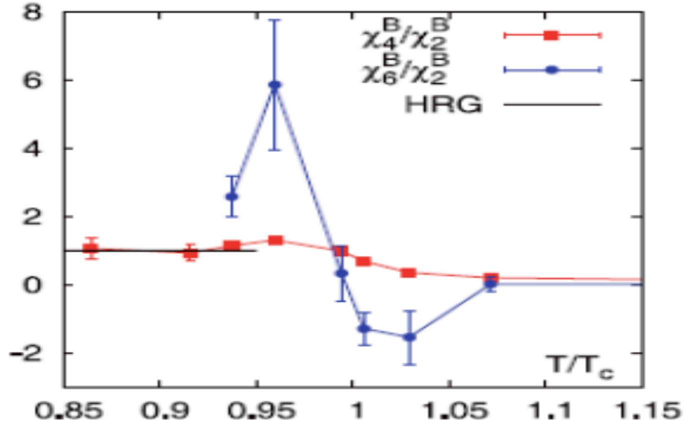


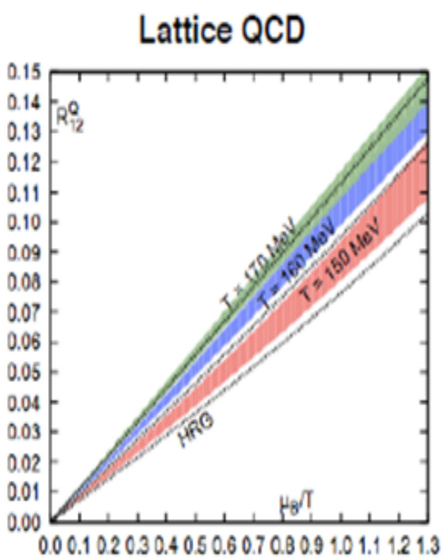


- Deconfined state of dense medium at RHIC top energy and LHC.
- Enhanced high pT (>2 GeV/c) production at lower energies.

Higher Moments of Conserved Quantities

- Susceptibilities and correlation length diverse near critical point
- Direct link between theory and moments of distributions



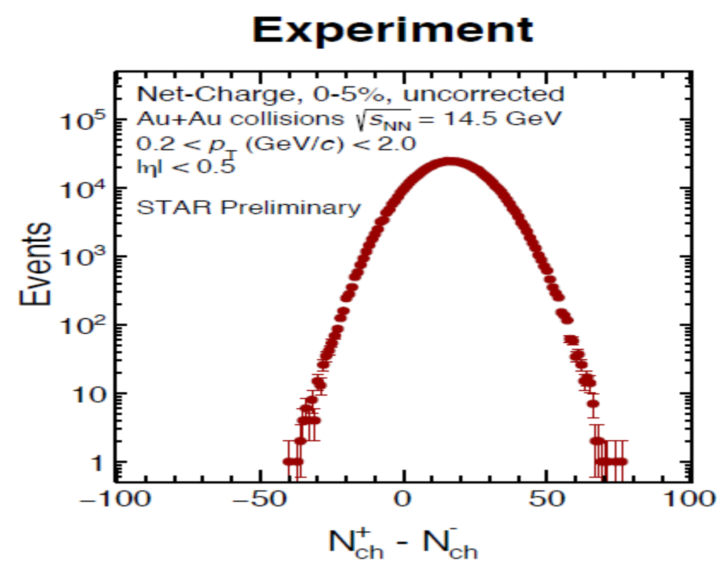


$$\frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i}$$

$$\frac{\chi_3^i}{\chi_2^i} = (S\sigma)^i = \frac{c_3^i}{c_2^i}$$

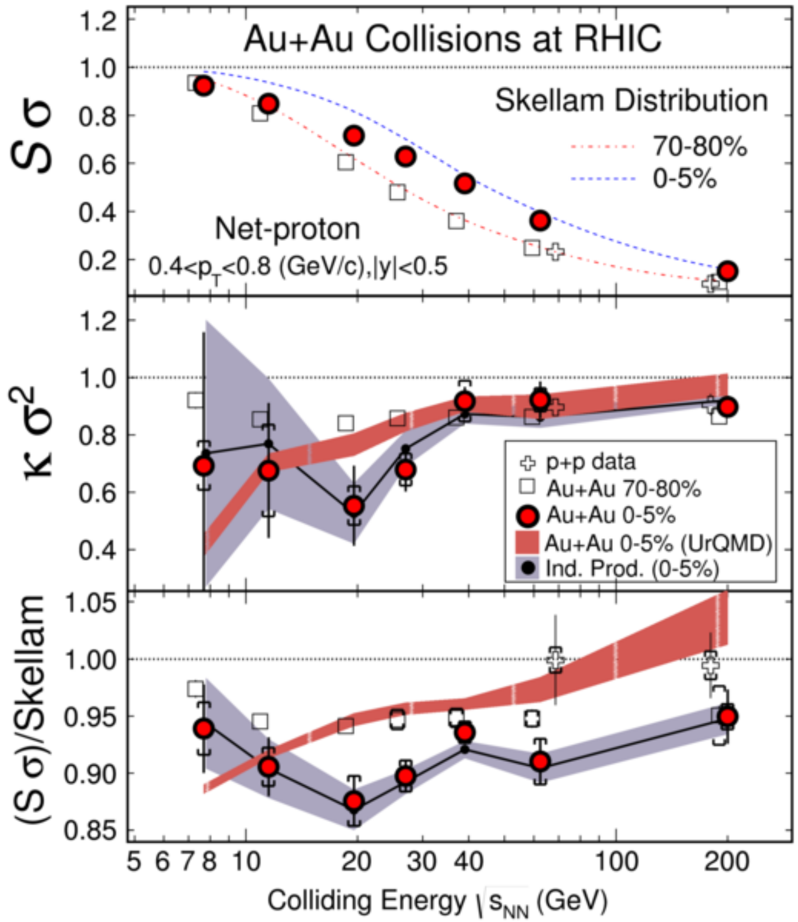
$$\frac{\chi_4^i}{\chi_2^i} = (\kappa\sigma^2)^i = \frac{c_4^i}{c_2^i}$$

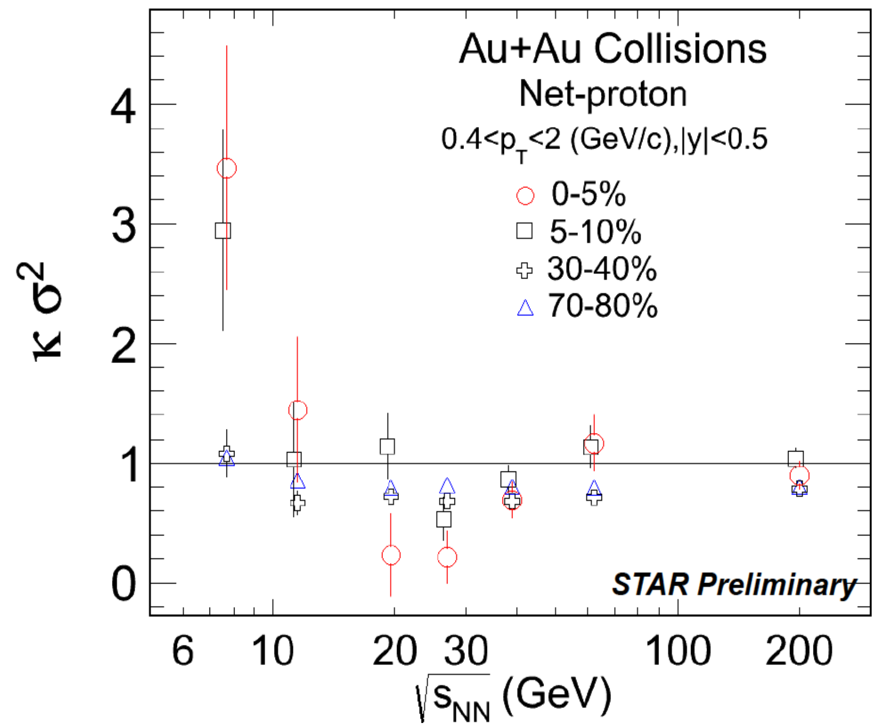
$$i = B, Q, S$$



Net Proton High Moments

STAR, PRL. 112, 32302(2014)

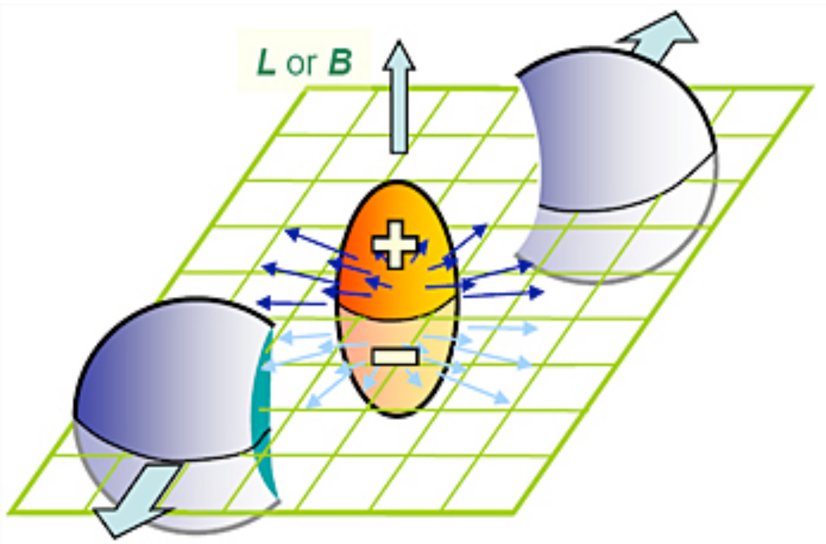


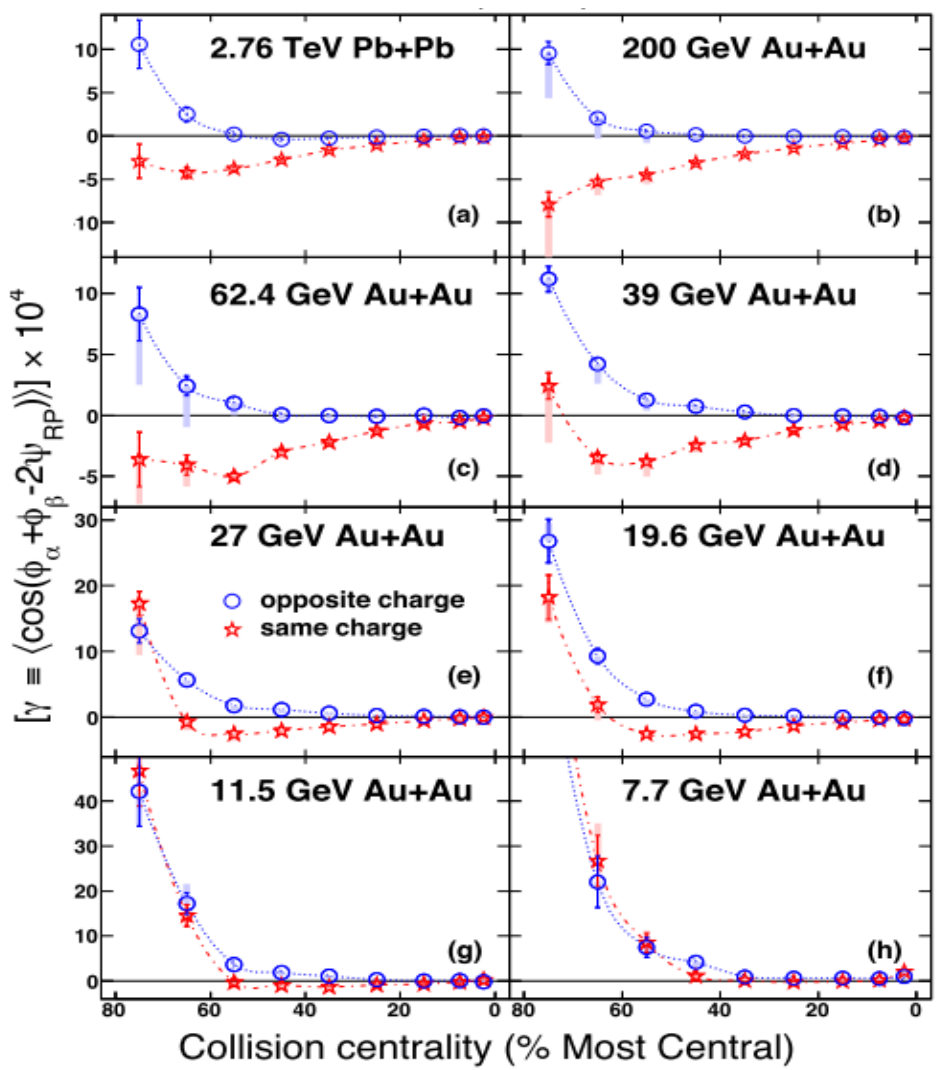


- For net-proton, from central Au+Au collisions, we observe non-monotonic behavior of susceptibilities
- Need more precise measurement below 20 GeV with finer steps in μ_B and increased rapidity acceptance

Charge Correlations

STAR, PRL, 113, 142301(2014)



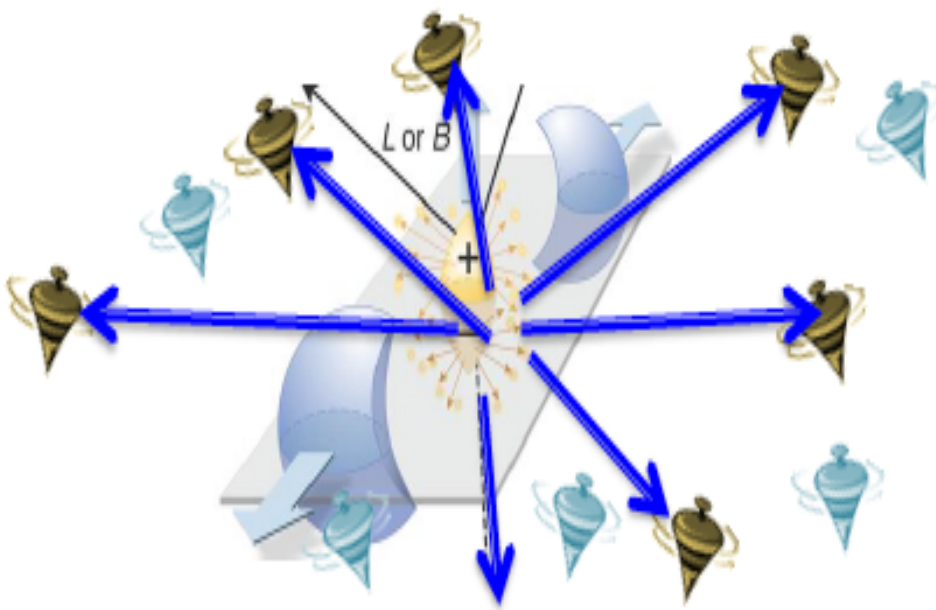


External Magnetic Filed: Charge separation, Chiral Magnetic Effect (CME)

Charge correlations vanishes at lower energies where haronic phase become dominant.

Global Λ Polarization

Large initial angular momentum: $|L| \sim 10^5\ \hbar$ in non-central collisions
Fluid vorticity may generate **global polarization**

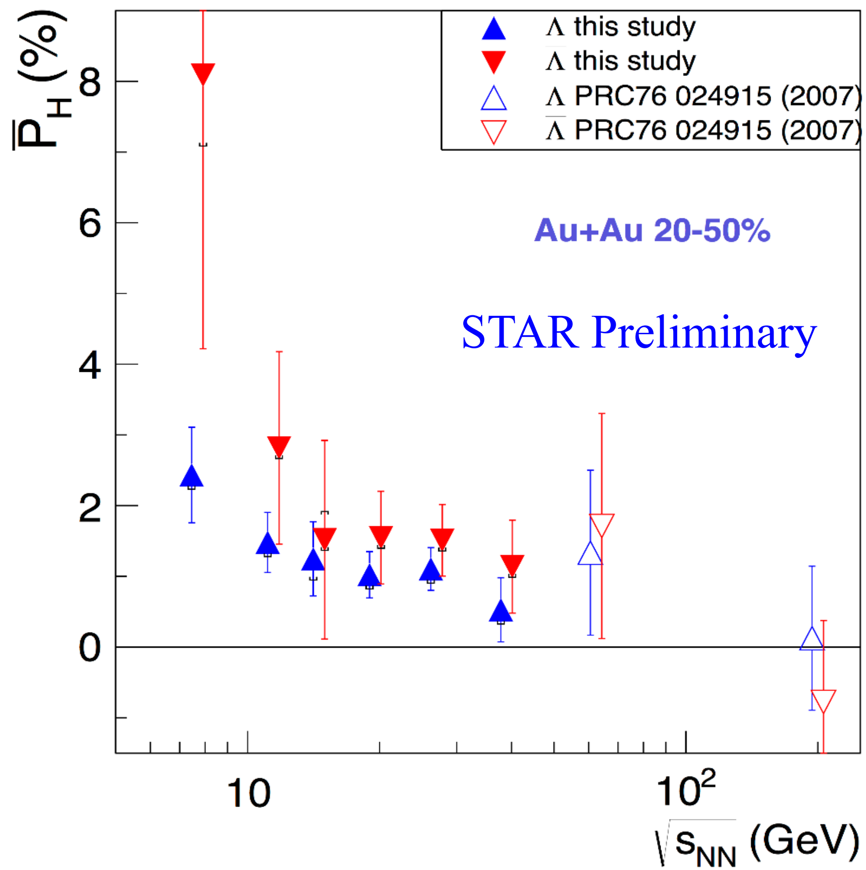


Using Lambdas :
Self –analyzing decay => preferentially emitting daughter protons in the spin direction
For AntiLambda spin is opposite to anti-proton direction

Global Λ Polarization

Acceptance integrated polarization

$$\overline{P}_{\mathrm{H}} = \frac{8}{\pi\alpha}\frac{\langle \sin(\phi_{\mathrm{p}}^{*} - \Psi_{\mathrm{EP}}^{(1)}) \rangle}{R_{\mathrm{EP}}^{(1)}}$$

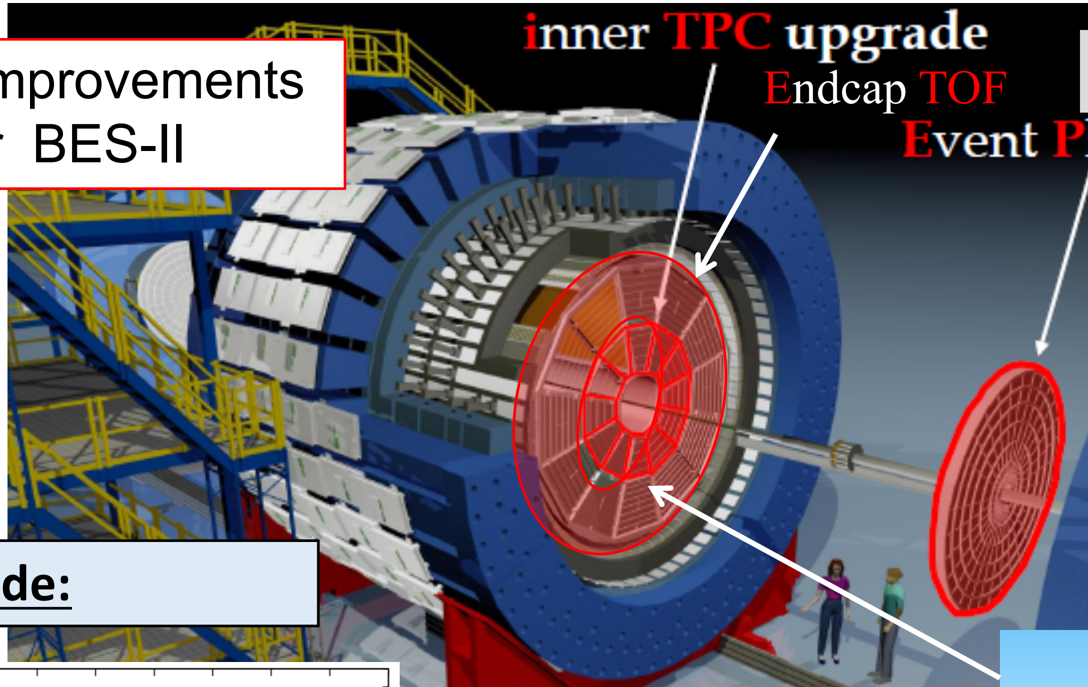


- First clear positive signal of global polarization in heavy ion collisions
- Both Lambdas and AntiLambdas show positive polarization.
- Allows Model-dependent estimate of B-field and hot and dense medium vorticity

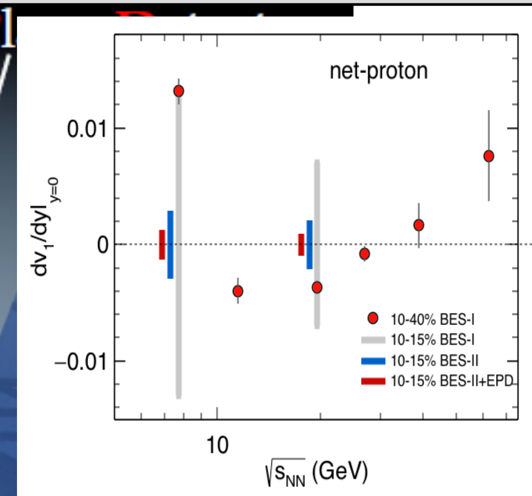
$\sqrt{s_{NN}}$ (GeV)	7.7	11.5	14.5	19.6	27	39
Λ	3.6σ	3.5σ	2.4σ	3.1σ	3.1σ	1.2σ
anti-Λ	-	2.1σ	1.1σ	2.4σ	3.0σ	1.7σ

The STAR Upgrades and BES Phase II

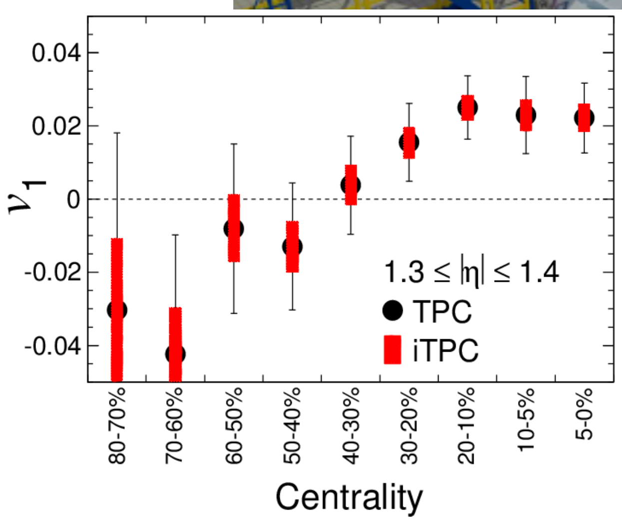
Major improvements for BES-II



EPD Upgrade:

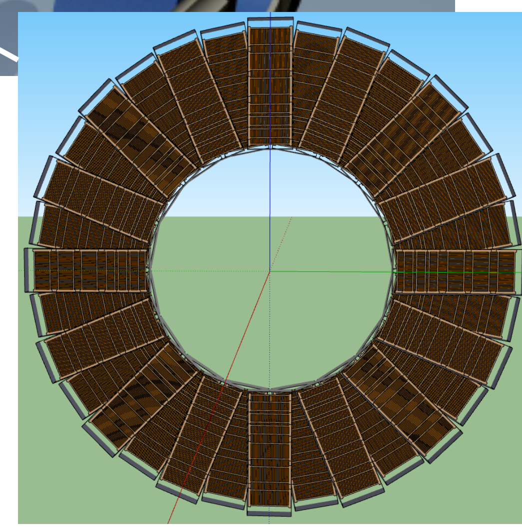


iTPC Upgrade:

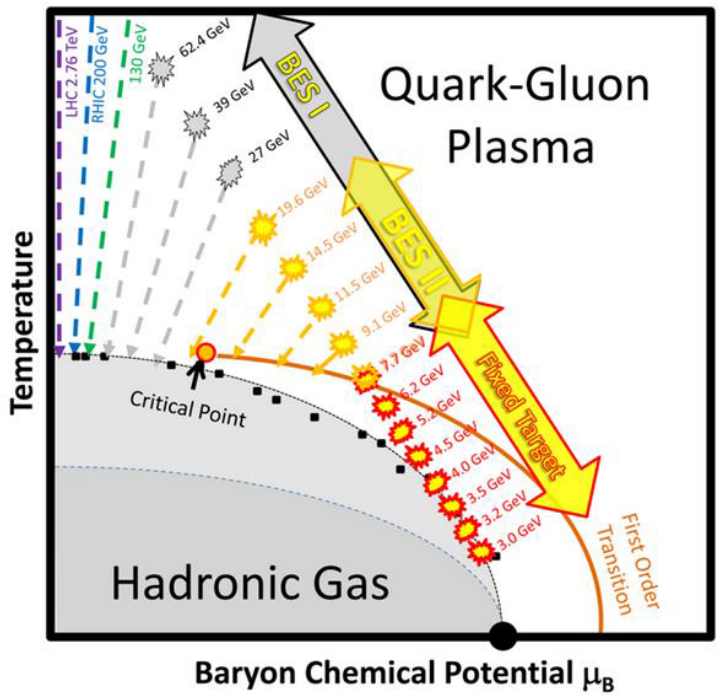


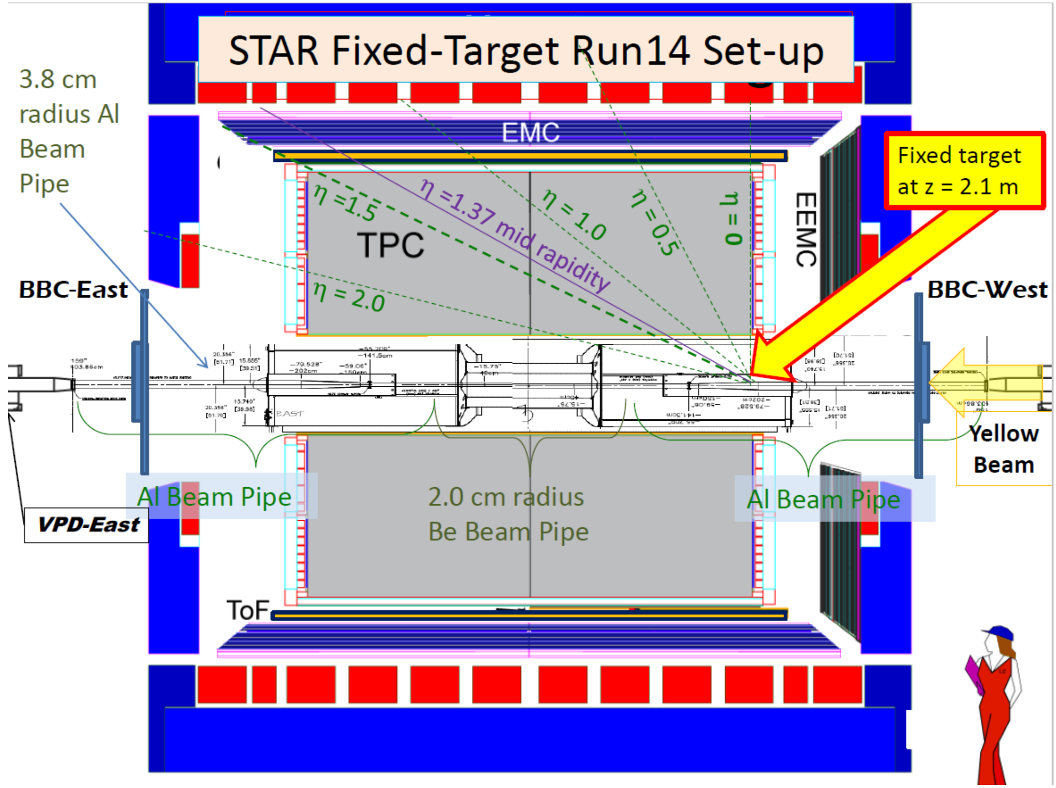
EndCap TOF Upgrade:

- Allows for PID in the h range provided by the iTPC upgrade
- eTOF needed for PID at forward rapidities

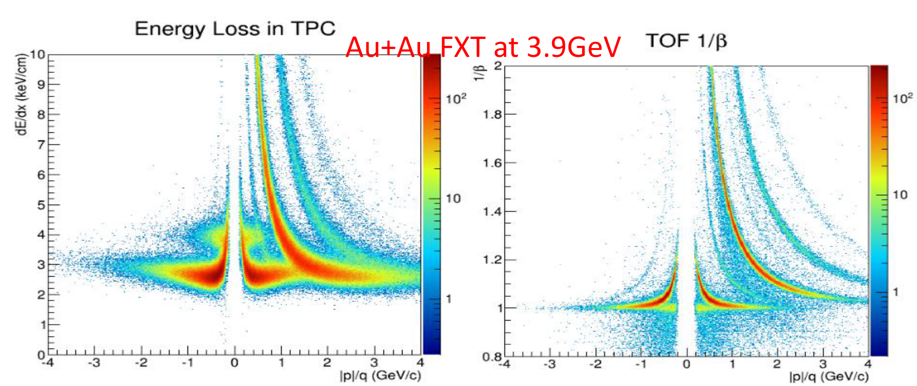


Fixed Target Program with STAR





- Extend energy reach to overlap/complementary AGS/FAIR/JPARC
- Real collisions taken in run 14 and results (K. Meehan @ QM15 & WWND16)
- Upgrades (iTPC+eTOF+EPD) crucial
- Unprecedented coverage and PID for Critical Point search in BES-II
- Spectra, flow, fluctuations and correlations



Summary/Outlook

- Spanning a range of μB that could contain features of the QCD phase diagram.
- Observed signatures consistent with disappearance of parton dominated regime.
- Indicators pointing towards a softening of the equation of state which is possible evidence for a first order phase transition.
- Critical phenomena – signal from higher moment fluctuations (Statistically demanding)
- Charge separation signal disappears at lower energy.
- First measurement of non-zero global hyperon polarization in heavy ion collisions.
- Beam Energy Scan II with fixed target program

  Many measurements in BES-II will allow us to pin down the location of a rapid transition in signals:

  HBT, v_n, Kurtosis, chirality (di-lepton, charge separation)

BACKUP

Planned BES II Measures

	Collision Energies (GeV):	**7.7**	**9.1**	**11.5**	**14.5**	**19.6**
	Chemical Potential (MeV):	**420**	**370**	**315**	**260**	**205**
	Observables	Millions of Events Needed				
QGP	R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
QGP	Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
QGP	Local Parity Violation (CME)	50	50	50	50	50
1st P.T.	Directed Flow studies (v_1)	50	75	100	100	200
1st P.T.	asHBT (proton-proton)	35	40	50	65	80
C.P.	net-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
EM Probes	Dileptons	100	160	230	300	400
	Proposed Number of Events:	**100**	**160**	**230**	**300**	**400**